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A discrepancy appears between the Mariner V and Venera 4 profiles of atmospheric parameters, if the Venera altitudes are transformed to radial distances, using the radar radius. This discrepancy is widely interpreted as a pure altitude discrepancy, arising from the altitude-radius conversion. This report studies the possibility that the apparent discrepancy may be a combination of true altitude errors, as well as errors in the mean polarizability of the atmosphere, related to the presence of unidentified polar constituents. Various explanations that attribute the entire discrepancy to altitude effects, are examined in the light of constraints imposed by other observational data. These explanations include: uncertainty in the region probed by Venera 4, possible elevated landing site, radar radius error, and surface radius variation. Aside from the apparent altitude discrepancy, there appears to be a small difference between the shapes of the Mariner refractivity and Venera number density profiles which, barring systematic experimental errors or significant revisions of the preliminary data, imply that the atmospheric polarizability may depend on altitude. The presence of unidentified polar substances could explain this dependence through the temperature dependence of their polarizabilities. The refractivity contributions from unidentified polar substances may be large, even if their number fractions are small. These substances may include particles of dimensions larger than ordinary molecules. Even if their mean dipole moment is zero, fluctuations in their charge distributions may still result in a large enough non-vanishing polarizability. Suggestions for further investigations are given.

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955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D. C. 20024

SUBJECT: A Review of Interpretations of the Mariner V-Venera 4 Discrepancy on the Venus Neutral Atmosphere

DATE: October 31, 1968

FROM: M. Luming

TM-68-1014-7

TECHNICAL MEMORANDUM

I. INTRODUCTION

The recent success of the Venera 4 and Mariner V missions to Venus has yielded a good deal of information concerning that planet. In particular, physical data concerning the lower neutral atmosphere have been obtained from both missions. In the case of Venera 4, the descent probe measured directly the pressure, temperature and density, and it also carried gas analyzers that sampled the atmosphere. Detailed reports on these measurements have recently become available.[1,2] They have elaborated and, in some instances, revised the preliminary information reported earlier in Russian newspapers.[3,4] In the case of Mariner V, the S-band radio occultation experiment measured essentially the refractive index of the atmosphere, from which pressure and temperature have also been derived.[5,6]

There is a widely recognized apparent discrepancy between the pressure and temperature profiles measured by Venera 4 and those deduced by Mariner V. The Mariner data are derived as functions of radius from the planet's gravitational center, while the Venera data are measured as functions of altitude above the surface. Using the average surface radius of 6056 km (see Sec. VII), as determined by radar time-delay[7], the Venera profiles can be expressed as functions of radius and compared with the Mariner profiles. This is shown in Figures 1 and 2 for the pressures and temperatures, respectively.[8] It appears that the pressure profiles of the two experiments differ by about 22 km, while the temperature profiles differ by 22 to 27 km, depending on the fractional abundance of CO_2.

The disagreement is a significant one, as it involves the consistency and correlation of three independent sets of measurements; namely, the radar time-delay, Mariner V, and Venera 4. The accuracies in all these experiments appear to be fairly high, and so far no serious errors have been found in any of them. There is a good probability that all three sets of data are essentially correct as they stand. If so, the discrepancy might be a manifestation of some physical characteristics of the planet that are not yet understood, which we might hope to track down by search-

ing for an explanation of the discrepancy. In analyzing the discrepancy, our approach is to identify the directly measured quantities of these three experiments, and to examine the various assumptions that are made in reducing the direct data to the final results.

II. DISCREPANCY IN TERMS OF REFRACTIVITY

The Mariner V experiment only measured directly one atmospheric property, the refractivity of the atmosphere. Therefore, it is informative to present both the Mariner and Venera results in terms of refractivity rather than in terms of pressure or temperature, which Mariner did not measure, and relate the Venera measurements to this parameter.

The refractive index of the atmosphere, denoted by $\tilde{n}$, is related to the number density n_i and polarizability α_i of its various constituents by the Lorentz-Lorenz formula:

$$\frac{\tilde{n}^2-1}{\tilde{n}^2+2} = \frac{4}{3}\pi \sum_i n_i\alpha_i . \qquad (2.1)$$

The polarizability is the proportionality constant between the electric dipole moment and electric field, which has the dimension of length cubed in the e.s.u. system. Throughout this paper, then, we will use cm^3 for α_i and cm^{-3} for n_i.

For $\tilde{n}-1<<1$, which is valid even in the dense atmosphere of Venus, the above formula is approximated by

$$\tilde{n} - 1 \equiv N = 2\pi \sum_i n_i\alpha_i \qquad (2.2)$$

where N is the refractivity. The above relation may also be expressed as

$$N = 2\pi n\bar{\alpha} \qquad (2.3)$$

where n cm^{-3} is the total number density, and $\bar{\alpha}$ cm^3 is the mean polarizability, defined by

$$\bar{\alpha} \equiv \frac{1}{n}\sum_i n_i\alpha_i$$

$$= \sum_i f_i\alpha_i . \qquad (2.4)$$

The quantity $f_i \equiv n_i/n$ is the number fraction, or molar fraction, or percent by volume, of the i-th constituent. (Frequently, we will use the notation f_{CO_2} to denote the number fraction of CO_2, etc.) It should be emphasized that the summations in Equations (2.1), (2.2) and (2.4) must include all the constituents in the atmosphere. By constituents, we mean not only the stable molecules that we normally think of as making up the neutral atmosphere, but also any other form of matter that may be suspended in it, such as aerosol particles.

The Venera 4 probe measured directly the temperature T and total pressure p. From these two measurements, the total number density can be determined from the perfect gas law:

$$n = \frac{p}{kT}, \qquad (2.5)$$

where k is the Boltzmann constant. This law is accurate within 1-2% for CO_2, N_2, and other common gases, in the ranges of pressures and temperatures encountered in Venus.[9]* Actually, the Venera probe also measured the mass density, from which the number density can also be derived. However, the density measurement is less direct, and hence less reliable, than the pressure and temperature measurements. (See page 7 for a discussion of the Venera density measurement.) Therefore, it is more accurate to derive the number density from the pressure and temperature data rather than from the readings of the density gage.

The relationship between the Mariner and Venera data is seen clearly in Eq. (2.3). Mariner V measured N as a function of r, the radius from the center-of-mass, whereas Venera 4 measured n as a function of z, the altitude above the surface. In relating N(r) and n(z), two factors have to be considered; (1) the transformation between r and z; (2) the mean polarizability of the atmosphere. Therefore, a disagreement between the Mariner and Venera data may arise from an erroneous assumption made about either (1) or (2), or both.

---

*Since about 90% of the total atmospheric pressure results from CO_2, the perfect gas assumption applied to the whole mixture is not very sensitive to possible deviation of a non-CO_2 species from a perfect gas. For example, a 40% deviation from perfect gas of some species whose number fraction is 5% will cause about 2% error in the assumption for the mixture. Whether a gas is polar or nonpolar, it will behave approximately like a perfect gas if its pressure and temperature are at some distance from its critical point. It is assumed that the low partial pressures ($\sim$ few percent of the total pressure) together with high temperatures will satisfy this condition sufficiently, so none of the other gases deviate too far (say, $< 40\%$) from perfect gas.

In Figure 3, the refractivity measured by Mariner is compared with that calculated from the Venera number density, based on a 100% CO_2 atmosphere. (If the latter is changed to 90% CO_2 - 10% N_2, the Venera curve in Figure 3 shifts slightly to the left, corresponding to a reduction of refractivity by a factor of .96.) The Mariner refractivity curve in Figure 3 corresponds to that from which the Mariner pressures of Fig. 1 and Mariner temperatures of Fig. 2 are derived. (see footnote 57) The radial distances of the Mariner profiles are converted to altitudes, assuming the zero altitude reference to be 6056 km. The direct inversion refractivity is used, since it is derived without assuming any a priori atmospheric model, other than spherical symmetry.

From Fig. 3, it is easy to see that there are two ways of looking at the discrepancy. It may be viewed as a discrepancy in altitude, or as a discrepancy in refractivity, or as a combination of both. The former view corresponds to errors in transforming radius to altitude, and the latter corresponds to possible errors in the assumed value for $\bar{\alpha}$. From the Mariner and Venera data alone, there is no way of determining how much of the discrepancy is due to either source of error.

It is, however, instructive to assume different values for the altitude error, and investigate the remaining discrepancy in terms of refractivity errors. Various altitude effects will combine to displace the lower and upper curves along the vertical axis resulting in a net vertical displacement of one curve relative to the other. This net displacement will be denoted by Δ; it has the same effect as changing the surface radius by an amount $\Delta r_o = \Delta$. It is a convenient parameter for representing the sum of all the altitude errors.

For a given value of Δ, the difference $\Delta N = N - 2\pi n\bar{\alpha}_o$ (see Eqs. 2.2 and 2.3) can be calculated as a function of altitude. It is the excess refractivity measured by Mariner V over that expected for an assumed mean polarizability $\bar{\alpha}_o$. In Fig. 4, ΔN is plotted for $\bar{\alpha}_o = \alpha_{CO_2}$. In terms of Eq. (2.2), the excess refractivity ΔN might be interpreted as the partial sum $2\pi \Sigma_i n_i \alpha_i$ of refractivity contributions that have been overlooked.

An alternative presentation of the excess refractivity is to consider the ratio of required $\bar{\alpha}$ to the assumed $\bar{\alpha}_o$, calculated by

$$\frac{\bar{\alpha}}{\bar{\alpha}_o} = \frac{N}{2\pi n\bar{\alpha}_o}, \qquad (2.6)$$

for a given value of Δ. Plots of this ratio are shown as solid curves in Fig. 5.

If the discrepancy were due solely to altitude effects, it should be possible to find a particular value of Δ that will yield an altitude independent value of $\bar{\alpha}/\alpha_o$ close to unity. It appears from Fig. 5 that this might not be the case.

The possibility that the assumed mean polarizability of the atmosphere could be in error is not obvious and has been largely ignored in current discussions about the discrepancy. One of the purposes of this report is to bring attention to this point. The possibility arises from the uncertainties in the non-CO_2 constituents of the atmosphere, and the magnitude of their refractivity contributions. In the following, we review the known facts about the composition of the Venus atmosphere, and indicate how the uncertainty in $\bar{\alpha}$ arises.

III. UNCERTAINTY IN COMPOSITION AND MEAN POLARIZABILITY

The Venera 4 gas analysis, as well as the earlier high-resolution spectroscopy by Connes et al.,[10], have confirmed CO_2 as the major constituent of the atmosphere. However, the CO_2 fraction is still uncertain. The best data available are those obtained by Venera 4, given in Table I. In the preliminary announcement,[4] Vinogradov gave $f_{CO_2} = .925 \pm .025$, but in a more recent report at the Kitt Peak Conference (March, 1968),[11] he revised it to $f_{CO_2} = .90 \pm .10$. Taken at its face value, the revised figure implies that the percentage of non-CO_2 gases may range from zero to 20%, with a probable value near 10%. Nevertheless, we cannot a priori assume that the refractivity contribution of the non-CO_2 gases is small, until we have identified all the non-CO_2 constituents, and ascertained the magnitudes of their individual polarizabilities.

The assumption is frequently made that all, or most, of the non-CO_2 gases consist of N_2. There is, up to now, no experimental support for such an assumption. Indeed, there is even no experimental evidence to date that positively confirms the presence of any N_2 at all. As indicated in Table I, the Venera 4 gas analysis only determined that, if N_2 were present, its abundance is less than 2.5%. In the preliminary announcement, the N_2 limit was given as 7%. As we now know, there were, not one, but two N_2 gas detectors on board; one has a threshold sensitivity of 7%, and the other a threshold of 2.5%. The readings of neither of these detectors exceeded the thresholds. Evidently, the preliminary report that $f_{N_2} < .07$ is a conservative estimate. If both detectors functioned properly, as implied by the final Russian report, the upper limit should be 2.5%. Prior to Venera 4, there were claims by Kozyrev[12] of detecting an airglow in Venus due to N_2^+.

However, these claims have been refuted by the observations of Weinberg and Newkirk,[13] and more recently, by Goody and McCord.[14] The present knowledge concerning N_2 may be summarized by the statement that $0 \leq f_{N_2} \leq .025$.

In Table II, we list the gases that have so far been positively identified and whose number fractions are known experimentally. These are CO_2, O_2, H_2O, CO, HCl, and HF. The fractions of CO, HCl, and HF are quite negligible, being, 9×10^{-4}, $.6 \times 10^{-6}$, and $.5 \times 10^{-8}$, respectively.[10] With regard to O_2 and H_2O, the Venera 4 measurements give $.004 < f_{O_2} < .016$, and $.001 < f_{H_2O} < .007$. On the other hand, the spectroscopic measurements give values about 10^2 times smaller for O_2,[15] and about 10^2 to 10^3 times smaller for H_2O.[10, 16, 17] At present, these discrepancies have not been resolved; therefore, when using the Venera data, we should keep in mind that the abundances of O_2 and H_2O may be much smaller.

Let us estimate the minimum fraction of unidentified gases implied by the existing data. The data give the following maxima for the identified non-CO_2 gases:

$$f_{N_2} < .025$$

$$f_{O_2} < .016$$

$$f_{H_2O} < .007$$

$$f_{CO} + f_{HCl} + f_{HF} < 10^{-4}$$

$$\text{Sum of above fractions} < .048 \qquad (3.1)$$

Denoting the total fraction of non-CO_2 gases by f_n, the Venera 4 data give:

$$\text{(Preliminary)} \quad .05 < f_n < .10 \qquad (3.2a)$$

$$\text{(Revised)} \quad 0 < f_n < .20 \qquad (3.2b)$$

Combining (3.2a) or (3.2b) with (1), we obtain the following ranges for the minimum value of f_X, the total fraction of unidentified gases:

$$\text{From (3.2a):} \quad .002 < (f_X)_{min} < .052 \qquad (3.3a)$$

$$\text{From (3.2b):} \quad 0 < (f_X)_{min} < .152 \qquad (3.3b)$$

These values are minima for f_X, as we have assumed a maximum value of .048 for the total fraction of identified non-CO_2 constituents. The estimate is conservative, because the value .048 is based on the Venera 4 maxima for O_2 and H_2O, and it also ignores the possibility that nitrogen may be absent. Because of the wide tolerances quoted for the value of f_{CO_2}, one is unable to specify a value for $(f_X)_{min}$. Nevertheless, it is reasonable to expect that $(f_X)_{min}$ probably falls in the vicinity of a few percent.

The preceding statement is reinforced by observational evidence from Venera 4, which suggests the possible presence of non-negligible fractions of unidentified gases which are neither CO_2, N_2, nor O_2. This suggestion arises from the anomalous behavior of the density measurement. During the first 50 minutes of the probe's descent, the density as well as pressure and temperature were measured simultaneously. The density reading was always larger than that expected for the pressure and temperature of either pure CO_2 or any mixture of CO_2, N_2 and O_2, which have mean molecular weights of 44.01 or less. The apparent mean molecular weight calculated from the density, pressure and temperature varies between 44.8 and 57, as shown in Figure 6. Although the possibility is not ruled out, the excess does not necessarily indicate that the unidentified molecules are heavier than CO_2.

The reason is that the density gage did not measure the mass density directly, but the ion current in a chamber where the atmosphere sample is ionized by electrons emitted from strontium - 90.[1] This current depends not only on the mass density but also on the ionizing and conducting properties of the mixture. As a density gage, it is composition-dependent, and must be calibrated beforehand for specific mixtures.

The Venera gage was only calibrated to measure the density of CO_2, N_2, O_2 and mixtures of these gases. The inconsistent gage readings may indicate that there are other gases present in the sample besides those for which the gage was calibrated. The Russian investigators think that these gases may be contaminations from the probe, but they may also simply be part of the atmosphere. A detailed analysis of the factors accounting for the inconsistent gage readings might throw some light on the nature of the unidentified gases.

The foregoing considerations indicate that there may be other unidentified non-CO_2 molecules, whose fractions may be of the order of a few percent. The polarizabilities of these molecules are unknown; therefore, their contribution to $\bar{\alpha}$, or to the total refractivity of the atmosphere, is unknown. If the polarizabilities are all of similar magnitude to that of CO_2 or N_2, their contribution would be limited, in view of their small fractions. However, we cannot a priori rule out large polarizabilities for the unidentified molecules. In which case, the value of $\bar{\alpha}$ assumed on the basis of a CO_2 - N_2 mixture may involve large errors. This will be discussed in Sec. V.

IV. REFRACTIVITY CONTRIBUTION OF THE AEROSOLS

Besides the refractivity contribution of unidentified molecules, there may also be a contribution from non-molecular constituents, such as aerosols. It is generally surmised that large quantities of particulate matter are suspended in the atmosphere of Venus. This is implied by many observational facts. For example, the planet's photometric phase curve, as well as its polarization phase curve,[18] exhibit features characteristic of light scattered from micron-sized particles rather than from molecules. There is also other evidence, such as the unusually high albedo, the diffuse appearance of the planet's terminator, the extension of the horns of the Venus crescent, etc.

The nature of the particulate matter is still unknown. Suggestions have been made that they may be ice or dust particles. Since the polarizability of a particle depends more strongly on its size than on the dielectric constant (see Eq.(A.2)), our calculation of the aerosol refractivity does not depend too strongly on the material we assume for the particles. In Appendix A, it is shown that the total refractivity due to particles with dielectric constant ε is given by

$$N_a(z) = \frac{3}{2} \frac{\varepsilon-1}{\varepsilon+2} \Phi(z), \qquad (4.1)$$

and that due to conducting particles is given by

$$N_a(z) = \frac{3}{2} \Phi(z) \qquad (4.2)$$

where $\Phi(z)$, defined in Eq.(A.5), is the total volume fraction occupied by the aerosols in unit volume of atmosphere. If, for example, we assume the aerosols to be dust particles, as in Öpik's aeolosphere model,[19] we could take ε to be about the same as that of the surface. The latter is derived from radar reflectivity,[20] which typically gives $\varepsilon = 3.7$. Thus, Eq. (4.1) reads $N_a = .71\Phi$. This differs by a factor of two from the case of conducting particles, but is of the same order of magnitude.

Clearly, the important parameter that determines the aerosol refractivity is the volume fraction of aerosols. Unfortunately, at present, this parameter is unknown. It is of interest to estimate the magnitude of Φ required, if all the excess refractivity were to be accounted for by aerosols. For simplicity, we assume the aerosol refractivity distributed exponentially with altitude:

$$N_a(z) = N_a(0)\, e^{-z/H_a}, \qquad (4.3)$$

where H_a is the aerosol scale height. This implies also that

$$\Phi(z) = \Phi(0)\, e^{-z/H_a}. \qquad (4.4)$$

The excess refractivity depends on the correction Δ applied to the altitude-radius conversion. A reasonable estimate for Δ to take care of various altitude effects may be, say, 15 km. For this case, Fig. 4 yields the following parameters:

$$\begin{aligned} N_a(0) &= 4.5 \times 10^{-3} \\ \Phi(0) &= 6.3 \times 10^{-3} \qquad \text{for } \varepsilon = 3.7 \\ H_a &= 12 \text{ km} \end{aligned} \qquad (4.5)$$

At $z = 18$ km, $\Phi \approx 10^{-3}$. This value may be compared with the volume fractions in terrestrial water clouds, which are in the range 10^{-7} to 10^{-5}, corresponding to observed liquid-water contents[21] of .1 to 10 g/m^3. Apparently, 10^{-3} appears to be an extremely large volume fraction by terrestrial standards. What would such a heavy aerosol content imply in terms of the opacity of the atmosphere to visible light, infrared and microwaves?

According to Eq.(A.13), for visible light, the vertical optical thickness of the atmosphere is given by

$$\tau \sim \frac{3}{2} H_a \Phi(0)/\bar{a}, \tag{4.6}$$

where $\bar{a}$ is the mean particle radius. For the case of the parameters in (4.5), we obtain

$$\begin{aligned} \tau &\sim 10^8 \text{ for } \bar{a} = 1\mu, \\ &\sim 10^7 \text{ for } \bar{a} = 10\mu. \end{aligned} \tag{4.7}$$

Such large opacities imply that practically no sunlight reaches the Venus surface. It would be pitch dark at the surface, as in the bottom of our oceans.

In the infrared, the wave lengths of interest are those near the peak of Planck's radiation curve for 600°K, where $\lambda \gtrsim 5\mu$. At these wavelengths, particle radii between 1μ and 10μ correspond to x between 1 and 10. At these values of x, Q(x) ranges from 1 to 5, assuming reasonable values for the complex dielectric constant.[22]* Therefore, the infrared τ differs from τ obtained above with Q(x) = 2 by less than a factor of 3, and the order of magnitude for the infrared opacity is about the same as that obtained in (4.7). Hence, the large concentration of aerosols required would make the atmosphere opaque to both visible and infrared photons. These conditions would prevent any greenhouse effect. Instead, the very large infrared opacity is sufficient to insulate the internal heat generated in the planet and account for the high surface temperature. According to Hansen and Matsushima,[23] an infrared optical thickness of the order 10^5 would be sufficient to give a 600°K surface temperature, if the heat outflow from Venus is of the same order as the Earth's ($\sim 10^{-6}$ cal/cm^{2}sec).

In the microwave region, x<<1, and Q(x) has the form[22]

$$Q_{sca}(x) = \frac{8}{3} x^4 \left|\frac{\varepsilon-1}{\varepsilon+2}\right|^2 \tag{4.8}$$

$$Q_{abs}(x) = 12x \frac{\varepsilon''}{(\varepsilon'+2)^2 + \varepsilon''^2} \tag{4.9}$$

*See Eq. (A.9) for definition of Q(x), the relative cross section.

for scattering and absorption, respectively. $\varepsilon = \varepsilon' - i\varepsilon''$ is the complex dielectric constant. Since $Q_{sca} << Q_{abs}$, $Q(x) \approx Q_{abs}$. Substituting (4.9) into (A.9) and (4.6),

$$\tau = \frac{18\pi\varepsilon''}{\lambda[(\varepsilon'+2)^2 + \varepsilon''^2]} \int_0^\infty dz\ \Phi(z) \qquad (4.10)$$

Hence, the microwave absorption coefficient of the aerosols is also proportional to the volume fraction. The question arises whether the large volume fraction required to account for all the excess refractivity would cause a microwave opacity that contradicts the observed relative transparency in the range of 3 to 20 cm.

The value of ε'' depends on the material of the aerosols, which is unknown. Moreover, it varies considerably, with the impurity content and the temperature.[24] So we can only make order of magnitude estimates. For example, if we assume the material to be fused quartz, $\varepsilon = 3.8(1 - 3\times10^{-4}i)$ at 520°K, neglecting the dependence of ε'' on wavelength. Assuming an exponential for $\Phi(z)$ in Eq. (4.10), and with $\Phi(0)$ and H_a given by (4.5), we obtain $\tau = 4.7$ for $\lambda = 3$cm, and $\tau = .7$ for λ 20cm. The value of ε'' used above is on the low side, as ε'' may range from 10^{-3} to .1 for various plausible materials.[26] If $\varepsilon'' = .1$, the values of τ would be roughly 100 times larger. It appears that the volume fraction required by the excess refractivity contradicts the radio emission data.

Conversely, the microwave transparency in the 3 to 20 cm region may be used to set an upper limit to the refractivity contribution of the aerosols. For this purpose, let us require $\tau<1$ for $\lambda>3$ cm. This gives the following condition from Eq. (4.10):

$$\int_0^\infty dz\ \Phi(z) < (\varepsilon'+2)^2/6\pi\varepsilon'' \qquad (4.11)$$

where $\varepsilon''<<(\varepsilon'+2)$ is assumed. Substituting (4.1) and (4.3) into the above, we obtain

$$H_a N_a(0) < \frac{(\varepsilon'+2)\ (\varepsilon'-1)}{4\pi\varepsilon''} . \qquad (4.12)$$

Fig. 4 indicates that the required scale height is in the vicinity of 12 km for the different curves. Assuming $\varepsilon' = 3$, we obtain

$$N_a(0) < .7\times10^{-3} \text{ for } \varepsilon'' = 10^{-3}$$

$$< .7\times10^{-4} \text{ for } \varepsilon'' = 10^{-2}.$$

According to Fig. 4, these values are $\sim$ 10 to 100 times too small to account for all the excess refractivity.

Aside from the difficulty in obtaining a large $N_a(0)$, there is also evidence against the required scale height of 10 to 14 km. From the photometry of the extended horns of Venus, Dollfus obtained an aerosol scale height of about 4 km.[18] This has been corroborated by Goody, who obtained a value of 3.7 km by combining spectroscopic data with refraction measurements.[27] If this value of scale height is used, the aerosol refractivity would drop off too rapidly at high altitudes to fit the data.

In the preceding discussion, we have relied on direct observational data rather than on theory. Any estimates of concentration from theoretical models of aerosol transport depend on too many unknown factors. Moreover, the assumptions of the models may not necessarily be valid. For instance, it is not certain that the gravitational sedimentation of the aerosols is opposed only by upward eddy diffusion. If aerosols are charged, large concentrations could be suspended by the action of electric fields. The general circulation of the planet is unknown, and it is possible that a steady flux of aerosols, carried with the flow, might maintain large concentrations of particles in the atmosphere. The sources and sinks for the particles, required in formulating the particle transport equations, are also unknown, as their production mechanism is unknown. By appealing directly to observational data, we have circumvented these uncertainties.

We have tacitly assumed above that each particle has no permanent dipole moment, so its polarizability is entirely due to its induced dipole moment, proportional to its volume. Actually, the nature of the Venus aerosols is unknown. It is quite possible that the particles may have permanent dipole moments. In that case, large refractivity contributions from the aerosols do not necessarily imply a large volume fraction. Further discussion of this point is contained in the next section.

V. REFRACTIVITY CONTRIBUTIONS OF POLAR CONSTITUENTS

It is shown in Section III that the existing observational data imply the possible presence of noticeable fractions of unidentified molecules. In this section, we investigate their possible effects on the interpretation of the Mariner-Venera discrepancy. The total fraction of such unidentified gases cannot exceed $\sim$10%, since the probable fraction of CO_2 is $\sim$90%. Therefore, the polarizability of the unknown gas must greatly exceed α_{CO_2} in order to have a significant effect on $\bar{\alpha}$.

Considerations in Appendix B show that any unidentified nonpolar gases are expected to have a minor effect on $\bar{\alpha}$. On the other hand, a polar constituent among the unidentified gases with a very large dipole moment, may increase the value of $\bar{\alpha}$ significantly even if its fraction is small. In the light of present experimental data, this should not be ignored in searching for an explanation of the Mariner-Venera discrepancy.

Actually, among the identified gases of Table II, there are already four that are polar; namely, H_2O, CO, HCl and HF. The number fractions of the last three molecules are extremely small, so their contributions to $\bar{\alpha}$ are very small, being of the order less than 10^{-3} times that of CO_2 (see Table II). If the maximum value for f_{H_2O} is .007, the contribution of H_2O at 300°K, according to Eq. (B.2), is given by

$$f_{H_2O}\,\alpha_{H_2O} \lesssim .07\,\alpha_{CO_2},$$

and will not have a large effect on $\bar{\alpha}$. Therefore, any significant contribution to $\bar{\alpha}$ will derive from polar molecules other than the above four molecules.

In the following analysis, we estimate the order of magnitude of the permanent dipole moments required to account for the excess refractivity. Define the average of the unknown moments squared by

$$\overline{\mu^2}_x \equiv \frac{1}{f_{xp}} \sum_i f_i \mu_i^2, \qquad (5.1)$$

where f_{xp} is the total number fraction of unidentified polar molecules, and the above summation is carried over the unidentified species only. Neglecting the aerosol contribution, and applying Eq. (B.3),

$$\bar{\alpha} = \sum_{\substack{\text{nonpolar}\\ \text{gases}}} f_i \alpha_i + \sum_{\substack{\text{identified}\\ \text{polar gases}}} f_i \frac{\mu_i^2}{3kT} + f_{xp} \frac{\overline{\mu_x^2}}{3kT} \qquad (5.2)$$

For our purpose, it is sufficient to consider an approximation of $\bar{\alpha}$ that is accurate to ~10%. In this approximation, the α_i's of the nonpolar, non-CO_2 molecules are assumed equal to α_{CO_2}, while the f_i's of the identified polar molecules are assumed to be zero, thus reducing (5.2) to

$$\bar{\alpha}(z) = (1-f_{xp})\ \alpha_{CO_2} + f_{xp}\ \frac{\overline{\mu_x^2}}{3kT(z)}$$

$$\approx \alpha_{CO_2} + f_{xp}\ \frac{\overline{\mu_x^2}}{3kT(z)} \qquad (5.3)$$

An important characteristic of the above equation is the variation of $\bar{\alpha}$ with altitude, resulting from the variation of temperature. Substituting the directly measured temperature profile of Venera 4 for T(z), one obtains a specific dependence of $\bar{\alpha}$ on z for a given value of $f_{xp}\ \overline{\mu_x^2}$. The quantity $\bar{\alpha}(z)/\alpha_{CO_2}$ thus obtained from (5.3) is plotted as dashed curves in Figure 5. These curves may be compared with the solid curves, showing the required $\bar{\alpha}(z)/\alpha_{CO_2}$ calculated from the Mariner and Venera data for different values of Δ. Accounting for the excess refractivity involves the nontrivial task of matching two functions of z; namely, the required $\bar{\alpha}(z)/\alpha_{CO_2}$ with that given by (5.3).

It is seen in Figure 5 that fair matches are obtained for the case with Δ = 10 km and $f_{xp}\ \overline{\mu_x^2} = 10^{-36}$ esu^2, and that with Δ = 15 km and $f_{xp}\ \overline{\mu_x^2} = .5 \times 10^{-36}$ esu^2.* A perfect match is hardly to be expected because of the approximations made and the many unknown factors involved. The altitude variation of the aerosol contribution may alter Eq. (5.3), but the exact manner of alteration is unknown. It is important to note that a very specific temperature function T(z) is used to determine both $\bar{\alpha}(z)$ and n(z). Whether the resulting product of these two functions can reproduce N(z) is not a priori guaranteed. That it can do so, if only qualitatively, attests to some degree of self-consistency in the physical model.

Assuming that the model is correct, the parameter $f_{xp}\overline{\mu_x^2}$ seems to fall in the range $.5 \times 10^{-36}$ to 10^{-36} esu^2. Unfortunately, the value for $\overline{\mu_x^2}$ cannot be determined since f_{xp} is unknown. Let us examine some possible cases:

*Throughout this paper, μ is given in electrostatic units, abbreviated by esu.

	f_{xp}	$\mu_{x,rms}$ in esu
Case I	.2	$1.6 - 2.2 \times 10^{-18}$
Case II	.1	$2.2 - 3.2 \times 10^{-18}$
Case III	.01	$7.1 - 10 \times 10^{-18}$

For comparison, we note that the dipole moment of H_2O is 1.85×10^{-18} esu. Case I is the extreme case admissible by the revised Venera data where 80% CO_2 is assumed (see Section III). In this case the required μ_x can be satisfied by a wide variety of polar gases.[28] In Case II, assuming a value of f_{xp}, the required μ_x tends to be too high for inorganic polar gases, but can readily be satisfied by many organic polar gases. In Case III, where only a small fraction of the non-CO_2 constituents are polar, the required μ_x is larger than the dipole moments of most ordinary polar molecules. The present uncertainty in f_{xp} does not allow us to draw any conclusions on the possible candidates for the unidentified polar molecules.

We like to point out that the dipole moments required in Case III, or when f_{xp} is even smaller, are not impossible to obtain. We note that a unit electronic charge (4.8×10^{-10}esu) at a distance of 1 Å already gives a moment of 4.8×10^{-18}esu. Therefore, it is expected that ordinary molecules, with dimensions of the order 1 Å, have dipole moments $\sim 10^{-18}$esu. On the other hand, objects with dimensions much larger than angstrom size, with charge distributions that are not perfectly symmetric, could easily give dipole moments much larger than 10^{-18}esu. In the following, we consider several possibilities for the nature of these objects.

One possibility is that these objects are simply part of the aerosols. Their true physical nature is still unknown, but some of the particles may have dipole moments, so that their contribution is similar to that of polar molecules; but their moments will be much larger because of their larger dimensions. For example, a pair of unit charges separated by a distance $\sim$.1 micron has a moment $\sim 10^{-15}$esu, many times the above requirement.

It is important to recognize that it is not necessary for the aerosol particles to have steady, permanent, dipole moments, in order to produce an effect similar to that of a true polar sub-

stance. It is known that dust and cloud particles pick up and loose ions in the atmosphere.[29] Such processes naturally lead to fluctuations in their charge distributions, which may yield a zero mean dipole moment, but a nonvanishing mean square dipole moment; i.e., $\overline{\mu} = 0$ but $\overline{\mu^2} \neq 0$. This results in a finite polarizability contribution. An analogous situation is observed in the case of proteins in solution; their polarizabilities come primarily from nonvanishing mean square dipole moments, caused by charge fluctuations of a similar nature.[30] In that case, dipole moments of the order 300×10^{-18} esu may occur.

Another possibility is that large dipole moments are carried by colloidal particles.[31] These are particles whose dimensions are larger than ordinary molecules, but small enough so that their surface area-to-volume ratios are extremely high. Their dimensions are found in the range 20 Å to .2μ. Their interfaces are usually characterized by the presence of surface charges, and their shapes are often asymmetric. Colloidal particles, as referred to here, are aggregates of molecules and not composed of single large molecules.

A third possibility is that these objects may be macromolecules. By this, we mean not exclusively complex macromolecules like proteins, nucleic acids, etc., with molecular weights in excess of 10,000, but also large molecules not connected with living matter, having molecular weights as low as ∿100, as for example, organic polymers. Dipole moments of macromolecules may range from ∿200 to 700×10^{-18} esu.[32] Their presence in very small fractions, $\sim 10^{-6}$, is sufficient to explain the Venera-Mariner discrepancy.

To reconcile the Mariner-Venera data, it is only required that the unknown constituent preserve its highly polar structure in the relatively cool upper regions of the atmosphere. Referring to Figure 3, if $\Delta = 15$ km, the altitudes explored by Mariner are above 20 km, where temperatures are less than 370°K according to the the Venera measurements. Therefore, the highly polar molecules do not necessarily have to be absolutely stable at temperatures up to surface temperature of 544°K. Indeed, the anomalous behavior of the Venera density measurement (Figure 6, and Section III) may indicate that at around 15 km altitude, where the temperature is around 400°K, some form of chemical transformation is taking place.

Whether small concentrations of large molecules are compatible with the chemistry of the cooler regions in the upper atmosphere, is a question which requires detailed investigation beyond the scope of this report. There are, however, some indications that chemical equilibrium with the lithosphere[33] is not the only

governing factor in the chemical structure of the atmosphere. The peculiar absorption spectrum in the ultraviolet,[34] and the observed decrease in ultraviolet albedo[35, 36] suggest the presence of more complex constituents.

A possible source of large carbon-containing molecules could be the reduction of CO_2 induced by energetic charged particles, similar to the processes demonstrated by Calvin, et al.[37] Such molecules can serve as precursors to more complex molecules.

There should be little difficulty in suspending macromolecules in the atmosphere. While they might be large, they are seldom larger than $\sim$.1 μ. Applying Stokes' law to the Venus atmosphere, one finds that a .1 μ particle with density of 1 g/cm^3 will take $\sim$100 years to fall 10 km by gravity. Moreover, aerosols that scatter visible light, which probably have sizes $\sim$1 μ, appear to be suspended indefinately in the atmosphere. The mechanism of suspension should be even more effective for smaller size objects.

In considering macromolecules, one need not a priori exclude those connected with living matter, for there is no definite proof that organisms are absent in the low temperature region of the Venus atmosphere. If the clouds are indeed ice crystals, [38,39] the prerequisites for photosynthesis, CO_2, H_2O, and sunlight, are plentiful in their vicinity. This has been emphasized by Morowitz and Sagan.[40]

In the foregoing, we have discussed different cases of finite values of f_{xp}. It is appropriate to inquire what type of fit $f_{xp} = 0$ would give. It is seen in Figure 5 that, with Δ = 22 km, a constant $\bar{\alpha}$ with $f_{xp} = 0$ fits the low altitudes, but does not fit the higher altitudes, where a variation of $\bar{\alpha}$ with altitude appears to be required. Since most of the Mariner data refer to the higher altitudes, the behavior in that region is of primary concern in interpreting the data.

The apparent variation of $\bar{\alpha}$ with altitude is implied by a small difference in shape between the Mariner and Venera refractivities. (Fig. 3) In the absence of more detailed information on possible error limits, it cannot be ruled out that the difference may be due to systematic errors. This point is in need of further investigation. The direct-inversion Mariner data, on which our analysis is based, are preliminary; therefore, conclusions based on the observed differences are tentative, pending the completion of final processing of the Mariner data.

Assuming the variation in $\bar{\alpha}$ to be real, we introduce an altitude dependence in $\bar{\alpha}$ by including the maximum of .7% water vapor, and this gives the dashed curve marked $f_{H_2O}\,\mu^2_{H_2O} = .024 \times 10^{-36}$ esu^2 in Figure 5. This dashed curve does not increase fast enough to fit the solid curve for Δ = 22 km. It appears that some additional polar constituents may be required to give enough variation of $\bar{\alpha}(z)$. This latter statement is subject to the assumption that the composition is invariant with altitude; i.e., the f_i's of the different constituents are constant. For if there is a condensible constituent, or one that may be produced in situ in the atmosphere, its number fraction may vary with altitude, causing a change in $\bar{\alpha}$.

VI. REGION PROBED BY VENERA 4

Let us now revert to the question of the displacement Δ, the other possible source of the Mariner-Venera discrepancy, and discuss in the following sections the several factors that can account for the displacement.

It has been surmised that the Venera capsule stopped transmitting data before it reached the surface, so the last temperature it read refers not to the surface, but to some higher altitude. In this case, the region probed by Venera 4 corresponds to higher altitudes, which reduces the discrepancies in Figures 1 and 2. The suspicion about a premature power termination is heightened by the fact that the power supply was designed to last for 100 minutes, and the total descent time of 94 minutes approached this limit.[3] Another argument advanced is that the microwave brightness temperature at wavelengths between 2 and 20 cm is around 600°K[41] which implies an average surface temperature in the range 650-700°K on account of the planet's emissivity. Looking at Figure 2, one notes that the Mariner temperature curve extrapolates to the expected range of temperature at the surface, whereas the Venera curve shows a surface temperature of 544°K, which appears to be too low. However, this argument may not hold if a small part of the observed microwave emission is of nonthermal origin, which by no means can be ruled out at present.

It was reported[2] that the radar altimeter did not monitor the altitude continuously, but marked only the initial altitude, which was found to be 26 $\pm$ 1.3 km. The subsequent alti-

tudes were obtained by subtracting the descent path from the initial altitude, which descent path was determined in two ways: (1) by integrating the hydrostatic equation using the density measured at various pressures; (2) by integrating the descent velocity, with the velocity calculated from the density and drag coefficient, neglecting vertical winds. The distances evaluated by these two methods agree very well. The total vertical path traversed by the capsule was found to be 28 ± 1 km, which agrees within 5% with the initial altitude. This, together with the fact that the signal stopped abruptly, lead the Russians to conclude that the capsule suddenly ceased transmitting at the moment of impact on the ground, and the final temperature measured was the surface temperature. The consistency of the data lends support to this conclusion. Serious error in measuring the initial altitude cannot be ruled out. An error of approximately 20 km is needed to account for the entire discrepancy.

VII. RADAR RADIUS

Another explanation of the discrepancy is that the radar radius may be in error. The basic experimental data in determing the radar radius are the travel times of radar signals reflected by the Venus surface, which have been measured at various times from 1959 to 1967. The radar travel time gives the distance between radar source and subradar point on Venus, to an accuracy of 1 part in 10^8, the accuracy of one-way travel time being of the order $\pm 5 \times 10^{-6}$ sec, equivalent to ±1.5 km in distance. The radius from the planet center-of-mass to the subradar point would be trivially and unambiguously determined if we could calculate, independently of the radar data, the instantaneous position of the planet center, to an accuracy comparable to the radar data. Unfortunately, this is not the case. (An exception will be discussed below). This is because the conventional astronomical constants used to calculate orbits are derived from optical observations, which are several orders of magnitude below the accuracy of the radar data. In fact, the most accurate method presently available for evaluating the astronomical constants is by radar measurement itself. Thus, both the planetary radius and the instantaneous position of the planetary center--therefore, the parameters used to determine the center's motion--must be determined simultaneously from the radar data. This was done by Shapiro et al.,[7,42] by obtaining a least-squares fit to a large set of radar observations from 1959 to 1966, supplemented by optical observations from 1950 to 1965. The procedure is briefly as follows:

First, the theoretical delay time at each radar observation is calculated, using the presently known values of masses

and orbital elements of the solar system. Among the parameters in this calculation is the Venus radius, assumed to be 6100 km. The residuals between the observed and theoretical time-delays are the Venus radius and 25 other parameters that enter into calculating the theoretical time-delays. The 25 other parameters are the inverse masses of Venus, Mercury, Earth-Moon and Mars, the earth-moon mass ratio, the astronomical unit in light-seconds, the Mercury radius, and six initial conditions each for the orbits of Mercury, Venus and the Earth-Moon barycenter. The final set of values for the 26 parameters represent the least-squares fit to about 330 radar and 1380 optical observations. Among the final set of parameters is the value 6056 km for the Venus radius.

A question naturally arises as to how much the correction of the Venus radius from 6100 km to 6056 km may be affected by adjustment of the other parameters. It turns out that the Venus radius adjustment is weakly correlated with all the other parameters, except the eccentricities of the Venus and Earth-Moon orbits, which have normalized correlation coefficients with respect to the Venus radius of about .5. The other parameters have correlation coefficients $<.26$, and are mostly $\sim.1$ or less. Therefore, the effect of the other parameters on the best-fit Venus radius is small.

It has been noted that a constant bias error in the measured travel time would lead to a change in the radar radius, without altering the least-squares fitting. However, this possibility is now considered remote, since the radar data obtained by each radar facility have recently been processed separately, and found to give about the same values:[43, 44]

Radar facility	Radar radius, km
Arecibo (Puerto Rico)	6052±2
Goldstone, Calif. (J.P.L.)	6053.7±2.2
Lincoln Lab. (M.I.T.)	6048±1

The most convincing evidence that the Venus surface radius does indeed lie in this range has recently been obtained by a group at JPL using the following approach. Ambiguities in determing the radius by radar are removed, if we can accurately determine the planet center at the time of radar bounce. Such a determination can be made on the basis of Mariner V range data during encounter. While no radar bounce was made at that exact time, there were radar bounces before and after that time, so an interpolation of radar data can indeed be made. The Mariner V range measurement is very accurate. The errors, mostly resulting from computation rather than instruments, are ~ 1 km. By combining the Mariner V range data with the radar data, a Venus radius of

6052.9 or 6055.8 was found, depending on the ephemeris used.

If a radar radius somewhat smaller than 6056 km is used in Fig. 3, the Mariner curve will be shifted upward, and the value of Δ for each curve in Figs. 4 and 5 is increased. A reduction in radar radius by 3 km, for example, will result in a uniform increase in Δ by 3 km, but the conclusions we derive will remain essentially unchanged.

VIII. POSSIBILITY OF ELEVATED LANDING SITE

A further possible explanation of the discrepancy is that Venera 4 landed on a mountain or plateau, 20-25 km above the mean surface level.

It was reported that Venera 4 landed "near the equator."[3] The report did not specify how close to the equator. But since the accuracy of locating the landing site is about 500 km (or ≈5°), "near the equator" probably means that the latitude is within ±5°.

More than 300 radar observations of Venus have been made on different dates over the past five years. Because the Venus spin axis is nearly normal to the ecliptic (∿1° off),[46, 47] the subradar points at the different dates of observations are all located very close to the equator and distributed at various longitudes around the planet. The radar illumination is, of course, not confined to the subradar point, but spread out over the hemisphere. However, a highlighted area may be identified about each subradar point from which approximately 50% of the radar echo power is reflected, and this area would cover roughly 7° in latitude and longitude.[48] The Venera 4 landing site is apparently located within more sensitive, radar-highlighted regions about the equator, which have been explored by numerous radar reflections. The reflections have been analyzed to determine surface features as summarized in the following:

a. Time-delay data - When the time-delays of many radar observations are least-squares fitted to a spherical model planet, a value for the mean equatorial radius is obtained. Furthermore, when the observed time-delay at each radar observation is compared to the theoretical value from the average spherical model, the difference may be interpreted as deviation of the radius of the subradar region from the mean radius. This is possible because of the high accuracy of the time-delay measurements, which is equivalent to about ±1.5 km in range. By examining the residuals of a large number of radar observations, Ash et al.,[7] concluded that the maximum radial variation in the equatorial region is about 4 to 5 km. This speaks

against the possibility of a 20-25 km plateau above the mean surface in the equatorial region. However, one might argue that a sufficiently small elevated area may have escaped previous radar detection. This argument may be resolved by future radar experiments that concentrate on the Venera 4 landing site.

b. Radar Surface Features - Several surface "features" on Venus have been detected by radar, but their physical nature has not been determined.[47, 49, 50] Their existence is inferred from the appearance of structures in the echo spectrum which move along the frequency axis, as a surface feature would move due to the planet's rotation. From the movement of the spectral feature, a simultaneous determination of the location of the surface marking and the rotation vector can be made. The most prominent of these features are the two regions now referred to as "Goldstone α and β", which have been well-confirmed by independent observers at successive inferior conjunctions. Their latitudes are at -33° and -25°, respectively; therefore, these two regions seem to be too far from the equator to be related to the Venera landing site. Other less-prominent surface features have been reported within less than 10° to the equator. At present, we can only conclude that the two most prominent features do not correspond to the Venera 4 landing site, but the possibility that one of the less prominent features coincides with the Venera 4 site remains open, which deserves further investigation.

But even if the location coincides, the cause of the spectral feature may be merely a region of higher dielectric constant, or of increased roughness. These spectral features show up with pronounced structure in the "depolarized" spectrum of returning waves that have reversed their circular polarization twice.[47] This indicates that some of the returning photons have been scattered, and raises the possibility of mountain ranges. However, fields of boulders or areas with roughness on the scale of a wavelength ($\sim$10 cm) could also produce similar effects.

c. Backscatter Function - The radar backscatter function of Venus resembles the lunar backscatter function at large incident angles, but is steeper at small incident angles.[49, 51] The latter indicates that the Venus surface is smoother than the moon's, a conclusion shared by all investigators. In terms of surface statistics,

the "mean slope" of Venus is about three times smaller than the moon's.[52] Therefore, the information from the backscatter function favors a planetary surface not as rugged as the moon's surface. At least, this applies to the equatorial region, where the radar incident angles are small. Hence, this piece of radar data does not favor the presence of 20-25 km mountains in the region where the Venera landing is located.

d. Variation of Radar Cross Section[48] - This variation may be attributed to the passage of changing terrain under the subradar region, but the fact that the variation changes with wavelength, makes it hard to interpret. This is complicated by possible absorption in the Venus atmosphere, as well as by the time variation of radar constants. No clear conclusion can be drawn from this aspect of the radar data.

From the above investigation, we find that the existing radar data, generally speaking, do not favor the presence of 20-25 km high mountains or plateaus in the region where Venera 4 landed. A concentrated program of radar reflections, aimed specifically at the landing site, to be made at the next opportunity, should provide a more definite answer.

IX. EXPLANATION IN TERMS OF VENUS FIGURE

Another possible explanation of the discrepancy is to attribute it to a variation of the surface radius due to the planet's shape. The points of tangency of the occulting rays during immersion are located at a latitude of 37°N, and during emersion are located at a latitude of 32°S. One might consider that the surface radius of about 6080 km, which is implied by the combination of Venera 4 and Mariner V data (assuming a CO_2 - N_2 atmosphere), refers to the 32°-37° latitude region, whereas the radar radius of 6056 km refers to the equator. This implies that the surface radius increases from the equator to the poles. Approximating the longitudinal section of the planet by an ellipse, we find that the polar radius would have to be about 66 km larger than the equatorial radius. This would be opposite to the shape of the earth, whose polar radius is about 21 km shorter than the equatorial radius.

On the contrary, there is recent experimental evidence from the Mariner V trajectory data indicating that Venus is oblate like the earth. This is implied by the gravitational potential derived from the Mariner V tracking data. Because the tracking is suspended during occultation, the available tracking data correspond to relatively long distances from the planet, and only the effect of the lowest order harmonic is observable.

This is usually denoted by J_2, a non-dimensional constant defined as follows:

$$V(r,\theta) = -\frac{GM}{r}\left\{1 - \frac{J_2 a^2}{2r^2}(3\cos^2\theta - 1)\right\} \qquad (9.1)$$

where $V(r,\theta)$ is the gravitational potential to order $(\frac{a}{r})^2$, a is the equatorial radius, r is the radius from the center of mass, θ is the colatitude angle, G is the gravitational constant, and M is the planet mass. The Mariner V tracking data show that for Venus[45]

$$J_{2\varphi} \approx .9 \times 10^{-5}.$$

We recall that for the earth,[53]

$$J_{2\oplus} = 1.0827 \times 10^{-3}.$$

The fact that $J_{2\varphi}$ has the same sign as $J_{2\oplus}$ means that Venus has an equatorial bulge like the earth, because J_2 is related to the moments of inertia of the planet by

$$J_2 = (C-A)/Ma^2 \qquad (9.2)$$

where C and A are the moments of inertia about the rotational and equatorial axis, respectively. The smallness of $J_{2\varphi}$ compared to $J_{2\oplus}$ means that the equatorial bulge of Venus is small.

In view of the above evidence, it is not possible to attribute the discrepancy to the shape of the Venus surface, since the radius of the mean surface level will be less at 32°-37° latitude than that at the equator.

Accepting the above value of J_2, the oblateness of Venus is much smaller than that for Earth. Assuming Venus's surface is an equipotential surface, we can derive the following relation between J_2 and the ellipticity ε,

$$J_2 = \frac{2}{3}\varepsilon - \frac{1}{3}\omega^2 a^3/GM \quad ,$$

where ω is the rotation rate.

We find that ε for Venus is 1.35×10^{-5}, compared to the value 3.35×10^{-3} for Earth, so the polar radius of Venus is less than .1 km smaller than its equatorial radius. Thus, there is a high degree of spherical symmetry, and this assumption used to invert the Mariner occultation data is valid. By explaining the Mariner-Venera discrepancy as partly due to polar substances, we preserve the spherical model, which is consistent with the information on J_2.

X. SUMMARY OF RESULTS

We have shown that the Venera-Mariner discrepancy may not be exclusively a matter of altitude differences, as tacitly assumed in current discussions, but may be a combination of altitude and refractivity errors. The latter arises from the uncertainties in the polarizabilities of the non-CO_2 constituents of the atmosphere. The discrepancy is, therefore, connected with the question of the complete composition of the atmosphere. The spectroscopic and Venera data on composition show that

1. An assumption that N_2 is the major non-CO_2 constituent is not supported by the observational facts.

2. The only gases positively identified are CO_2, CO, O_2 H_2O, HCl and HF, but the present observational data allows the possible presence of other unidentified molecules, whose number fractions may be of the order of a few percent.

The possible effects on refractivity of the presence of unidentified molecules that are polar can account for part of the discrepancy. For reasonable values of number fractions of such constituents, the required dipole moments can be met by various polar substances. An important feature of a large refractivity contribution from polar sources is the variation of the atmosphere's mean polarizability with altitude. Barring the possibility of systematic experimental errors, such a variation appears to be present in the data. Our analysis is based on Mariner data that are still preliminary; therefore, our conclusions are tentative, pending the completion of final processing of the Mariner data.

The possible refractivity contribution of aerosols has been investigated. If their contribution is limited to the induced polarizability determined by particle volume, the concentration of aerosols required to account for the discrepancy is excessive, and contradicts the observed data on microwave emission, and the photometry of the extended horns of Venus. However, the possibility that fluctuation of charge distribution in the aerosol particles may yield a very large mean square dipole moment, even though the mean dipole moment is zero,

would permit the aerosols to behave effectively like large polar substances, and their refractivity contribution can be comparable to, or larger than, that for polar molecules.

We have explored the various explanations that interpret the discrepancy as a pure altitude effect. These include the posibilities of Venera 4 altitude error, elevated Venera landing site, radar radius error, and variation of surface radius due to the planet's shape.

The present radar data suggest a small likelihood that Venera 4 landed on an elevated site, about 20 km above the mean surface level. However, a moderate elevation of 5 to 10 km may well be consistent with the data. A more definite conclusion may be drawn from improved radar data, specifically aimed at exploring the landing site.

A critical examination of the procedure by which the radar radius is arrived at, indicates that its value should represent the mean surface radius in the equatorial region. The agreement among several independent determinations shows that the value lies in the range 6050-6056 km.

The variation of surface radius needed to explain the discrepancy requires a prolate spheroid of large ellipticity, which contradicts the Mariner V tracking data. Such an explanation is not acceptable.

XI. CONCLUSIONS AND RECOMMENDATIONS

The studies summarized above suggest that it is premature to treat the Mariner-Venera discrepancy as being entirely an altitude effect. There are differences between the Mariner and Venera data which, barring systematic experimental errors, could imply that the atmospheric polarizability depends on altitude and temperature. The presence of noticeable amount of unidentified polar substances could reconcile these differences. Within the constraints of the available observational data on Venus, it is possible that a part of the discrepancy is caused by the presence of large polarizabilities of some non-CO_2 constituents. Because such large polarizabilities have important implications on the nature of the Venus atmosphere, it is advisable to pursue further research that can help clarify the discrepancy. As examples of further work, we list here a number of suggestions that have emerged from our studies:

1. Concentrated radar measurements, made at a future conjunction when the Venera landing site is again near the subearth point, may be able to examine evidence for 20 km elevations in the vicinity of the landing area.

2. An investigation of the possible causes of the anomalous behavior of the Venera density gage may provide a clue to the nature of the unidentified non-CO_2 constituents.

3. A better definition of the number fraction of CO_2 will help to resolve the uncertainty in the total fraction of non-CO_2 constituents.

4. Spectroscopic search for non-CO_2 constituents in unexplored spectral regions should be continued. In particular, the unexplained ultraviolet absorption should be investigated more carefully.

5. Continued effort in the study of the microwave spectrum at high resolution--such as by means of radio interferometry--and over as wide a spectral range as possible, should eventually help determine the mean surface temperature.

6. It may be desirable to investigate the possible mechanisms by which aerosols may acquire a mean square dipole moment through fluctuations of their charge distribution, even though the mean dipole moment is zero.

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Max Luming

M. Luming

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Attachments
Tables 1 & 2
Figures 1 thru 6

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57. We calculated the Mariner refractivity from the direct inversion, night-side, pressure and temperature curves for 100% CO_2. The pressure curve is shown in Fig. 1, and is identical to Fig. 6(b) in Reference 5. The corresponding temperature curve is shown in Fig. 2. Refractivity points are calculated at the radial distances corresponding to the break points of the temperature curve. The Mariner refractivity profile in Fig. 3 is an average curve through these calculated points. Recently, Kliore and Cain (Reference 55) reported revisions in the Mariner radial distance scales due to time corrections. These revisions resulted in an approximately uniform altitude shift in the "pseudoinversion" profiles. If a similar uniform shift is also required for the direct inversion profiles, the numerical values of Δ in our analysis will be changed by a constant amount.

TABLE I

VENERA-4 GAS ANALYSIS

GASES*	(1) f (preliminary)	(2) f (final)
CO_2	.90 - .95	.80 - 1.00
O_2	.004 - .008	.004 - .016
H_2O	.001 - .007	.001 - .007
N_2	<.07	<.025
unidentified gases	0 - .10	0 - .20
H_2	---	$H_2 + O_2 < .016$

(1) Preliminary results given by Vinogradov in Reference 4.

(2) Final results presented by Vinogradov at Kitt Peak Conference, March 1968. (See Reference 11)

*There were 11 gas analyzer cartridges used but some are redundant. The system is designed only to detect five gases CO_2, N_2, H_2O, H_2 and O_2.

TABLE II

MOLECULES POSITIVELY IDENTIFIED IN THE VENUS ATMOSPHERE

	μ 10^{-18} esu	α 10^{-24} cm^3	f
CO_2	0	2.92	.90 ± .10
O_2	0	1.57	.004 - .016 (Venera 4) < 10^{-5} (Spectroscopy)
H_2O	1.85	$1.51 + \frac{8270}{T}$	.001 - .007 (Venera 4) 10^{-5} - 10^{-7} (Spectroscopy)
CO	.10	$1.85 + \frac{24}{T}$	.9 x 10^{-4}
HCl	1.07	$2.77 + \frac{2770}{T}$	.6 x 10^{-6}
HF	1.91	$? + \frac{8810}{T}$	.5 x 10^{-8}

α and μ are based on data from Reference 28,

T is temperature in °K.

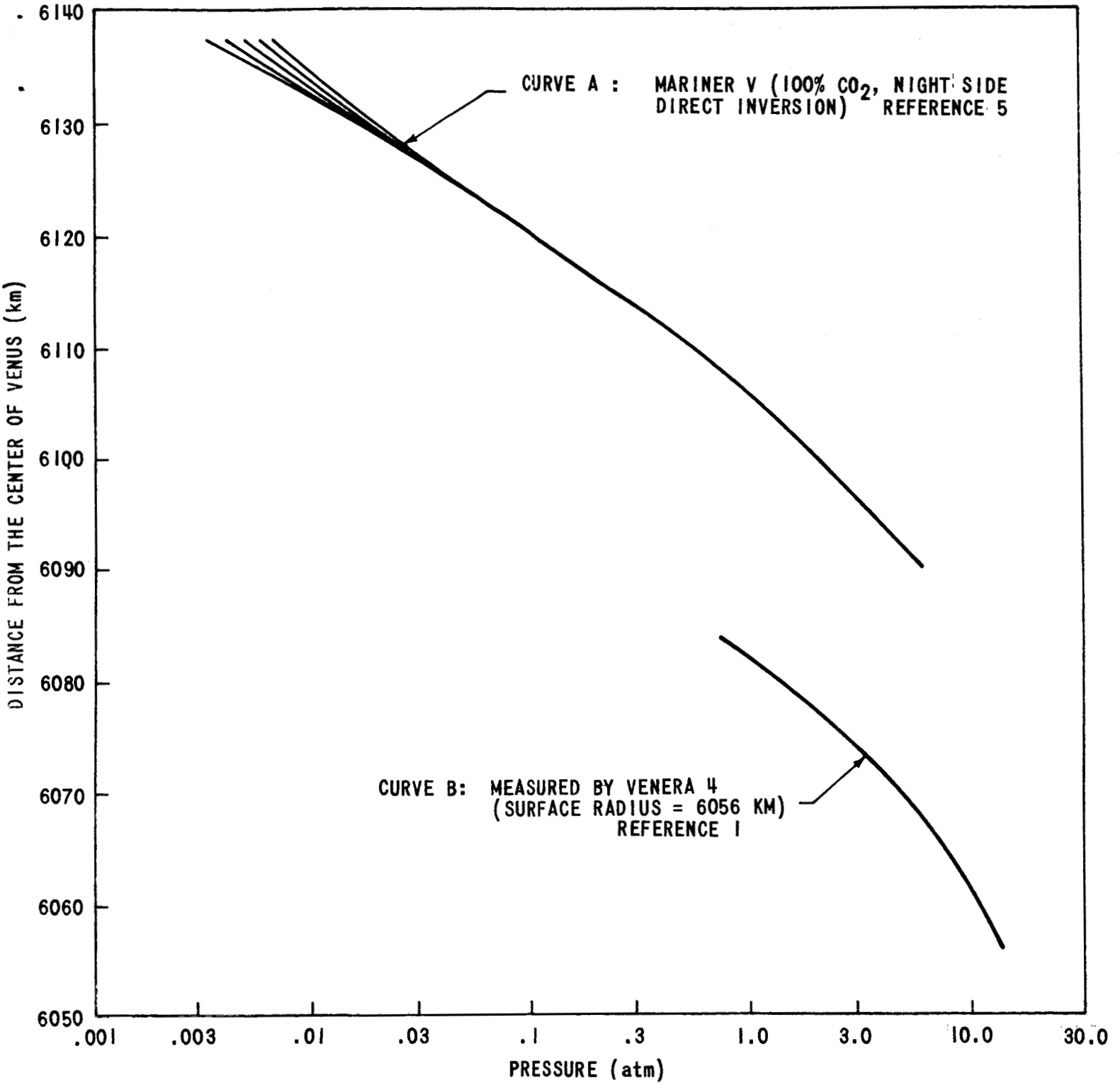

FIGURE 1 - COMPARISON OF PRESSURES

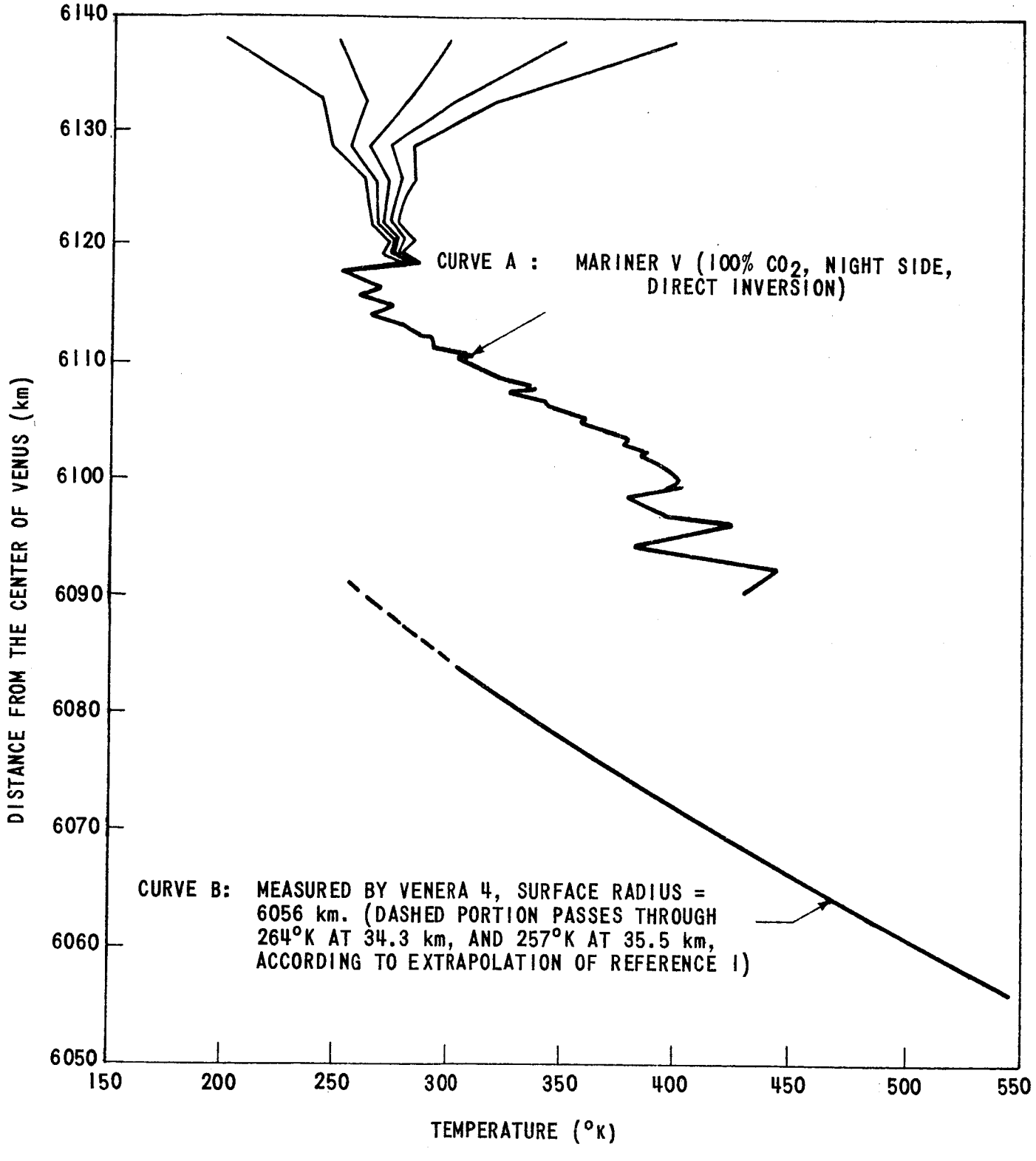

FIGURE 2 - COMPARISON OF TEMPERATURES

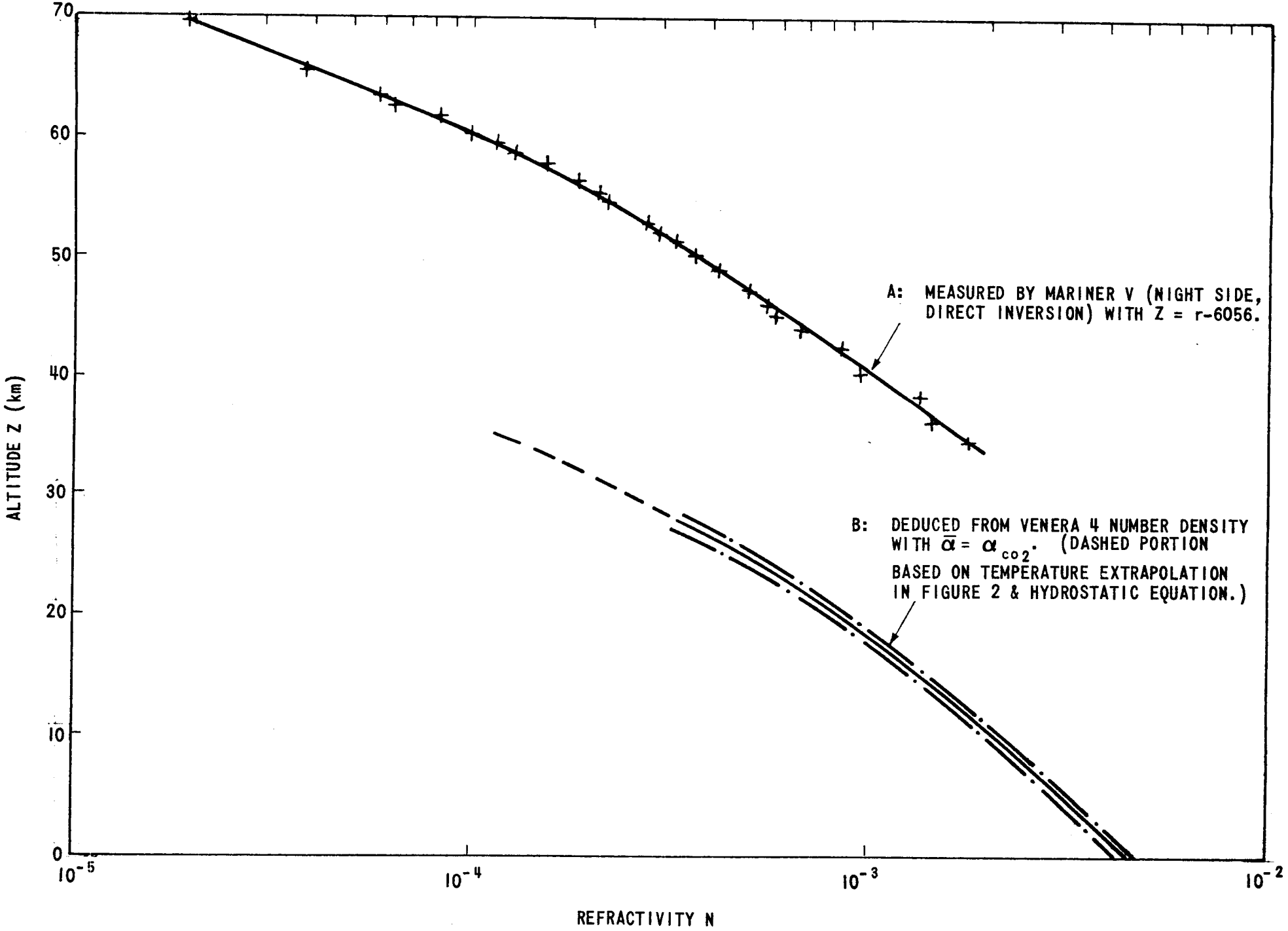

FIGURE 3 - COMPARISON OF REFRACTIVITIES

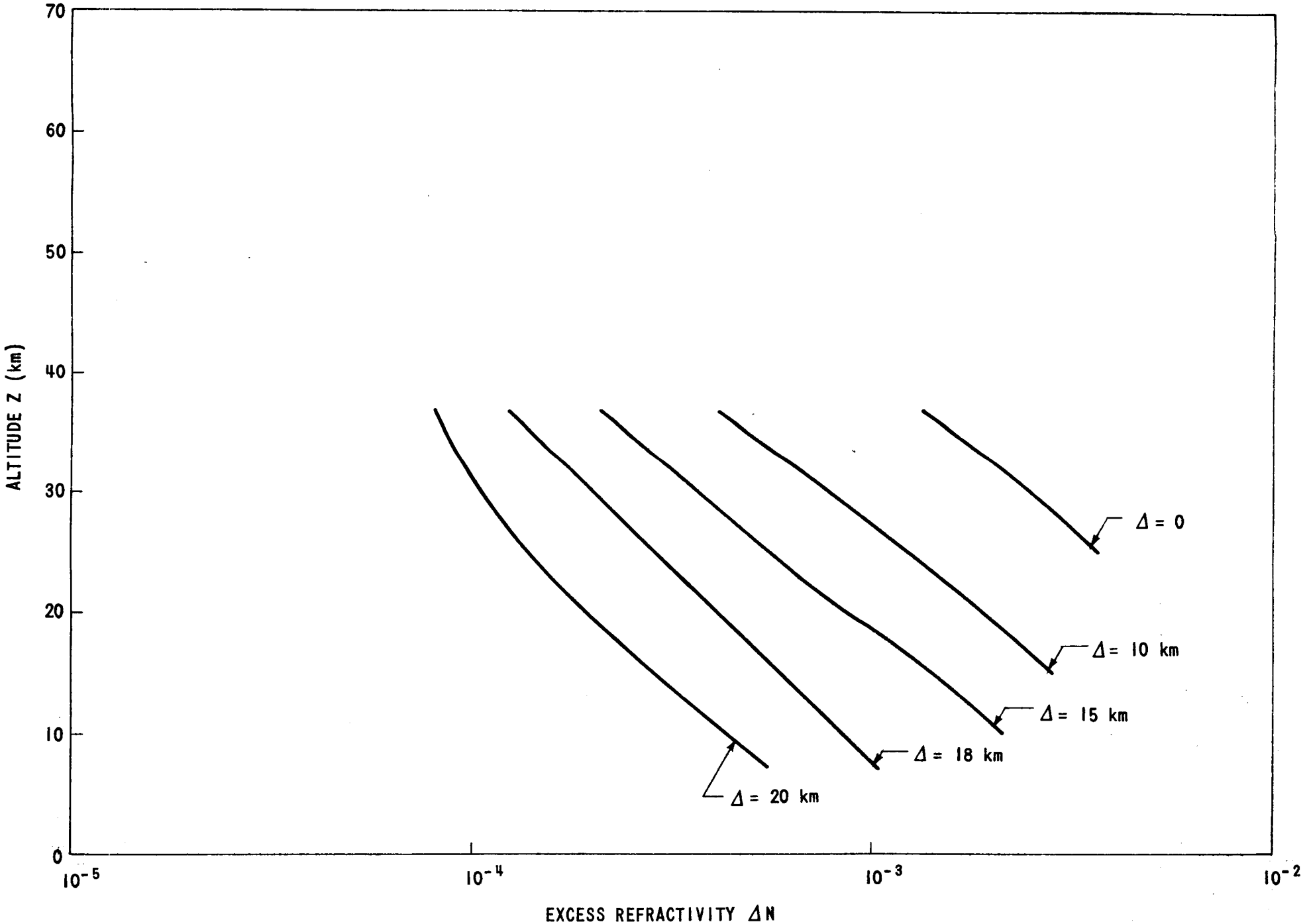

FIGURE 4 - EXCESS REFRACTIVITY ΔN VERSUS ALTITUDE AS FUNCTION OF DISPLACEMENT Δ.

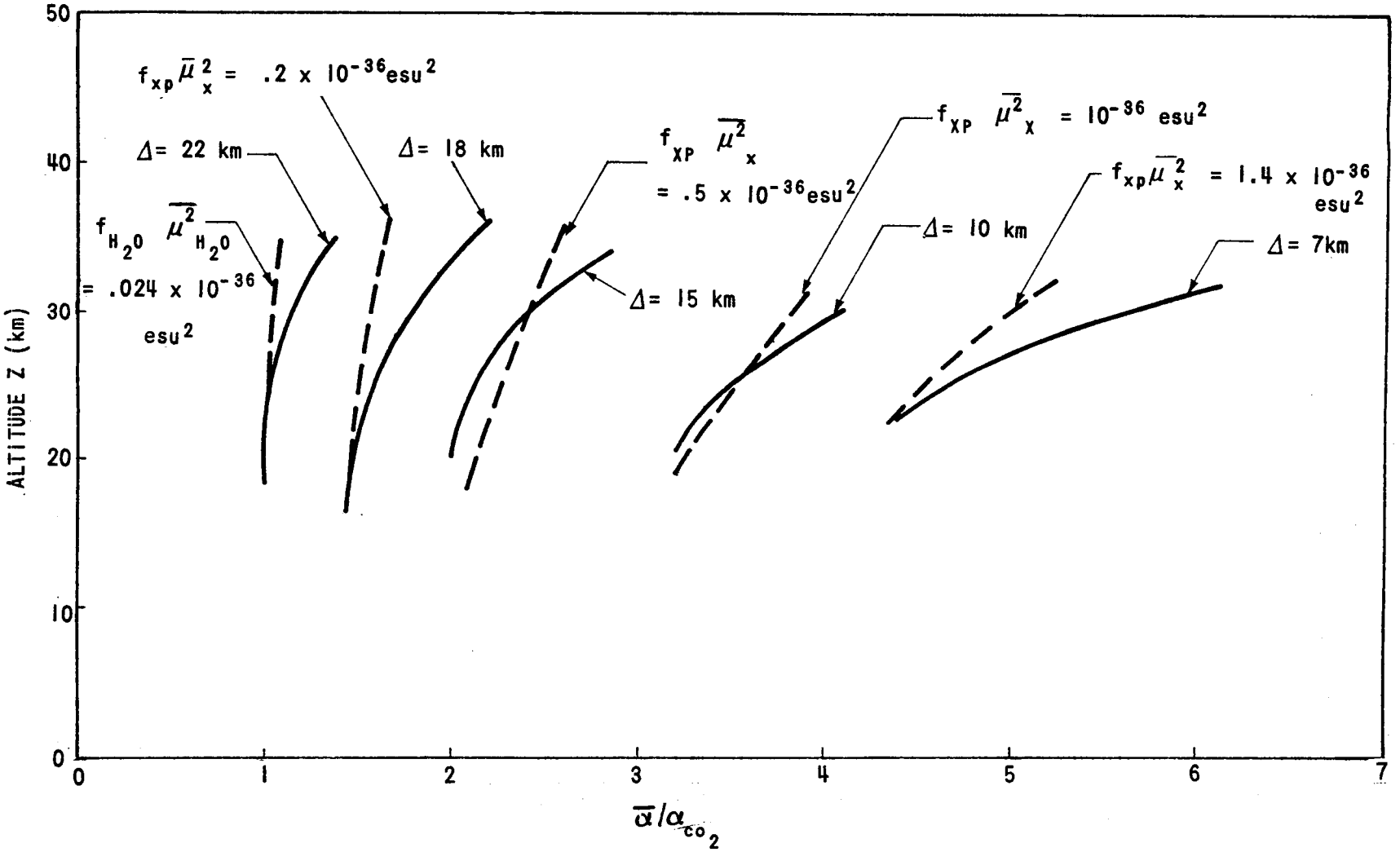

FIGURE 5 - $\overline{\alpha}/\alpha_{co_2}$ VERSUS ALTITUDE.

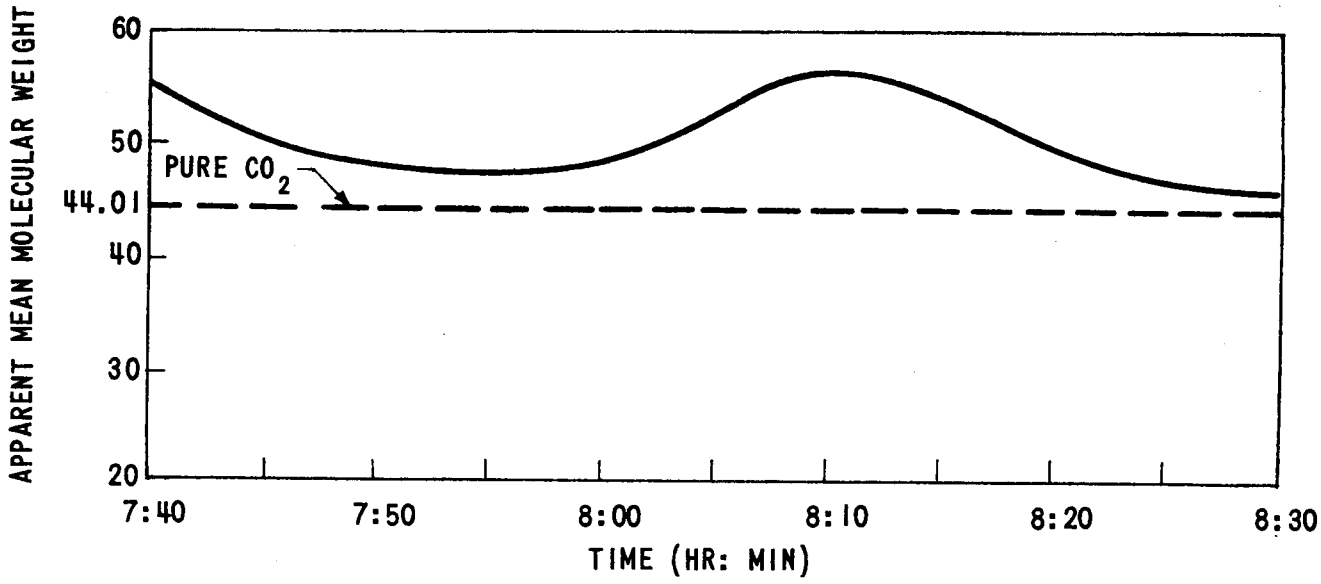

FIGURE 6 - APPARENT MEAN MOLECULAR WEIGHT, CALCULATED FROM VENERA 4 DENSITY, PRESSURE, AND TEMPERATURE. (AFTER REF. 1)

APPENDIX A

ANALYSIS OF AEROSOL REFRACTIVITY

When a conducting sphere of radius a is placed in an electric field $\tilde{E}$, a dipole moment $a^3\tilde{E}$ is induced in it. Hence, the induced polarizability of a spherical conducting particle is*

$$\alpha_a = a^3 \tag{A.1}$$

For a spherical particle of dielectric constant ε, a similar expression holds:

$$\alpha_a = \left(\frac{\varepsilon-1}{\varepsilon+2}\right)a^3 \tag{A.2}$$

For probable values of ε, the factor in parenthesis is of order unity; therefore, in either case, α is of order a^3.

From the above relations, we can readily understand the vast difference between the induced polarizability of a molecule and that of a micron-sized particle. The former resembles a conducting sphere with a radius $\sim 10^{-8}$ cm, so its induced polarizability is $\sim 10^{-24}$ cm^3. On the other hand, a particle of 1μ radius has $\alpha \sim 10^{-12}$ cm^3, which is many orders larger than that for a molecule.

If $n(a,z)da$ is the number density of particles with radius between a and a + da, located at the altitude z, then, according to Eqs. (A.2) and (2.2), the total refractivity due to the aerosols is

$$N_a(z) = 2\pi \frac{\varepsilon-1}{\varepsilon+2}\int_0^\infty n(a,z)a^3 da \tag{A.3}$$

where, for simplicity, the aerosols are assumed to be dielectric spheres with an average dielectric constant ε. The integral in (A.3) is proportional to the total volume fraction occupied by the aerosols in unit volume of atmosphere. If we denote the latter by Φ, the above relation reduces to

$$N_a(z) = \frac{3}{2}\frac{\varepsilon-1}{\varepsilon+2}\Phi(z), \tag{A.4}$$

where

$$\Phi(z) \equiv \frac{4\pi}{3}\int_0^\infty n(a,z)a^3 da. \tag{A.5}$$

---

*Gaussian units will be used throughout.

The vertical optical thickness of the atmosphere is

$$\tau = \int_0^\infty dz \int_0^\infty da\ n(a,z)\ \sigma(a,\lambda) \qquad (A.6)$$

where $\sigma(a,\lambda)$ is the total extinction cross section per aerosol particle, λ being the wavelength. If the aerosol size distribution is independent of altitude, $n(a,z)$ may be assumed to be of the form

$$n(a,z) = n(a,0)\ e^{-z/H_a} \qquad (A.7)$$

Eq. (A.6) becomes

$$\tau = H_a \int_0^\infty n(a,0)\ \sigma(a,\lambda)\ da. \qquad (A.8)$$

In general,[22]

$$\sigma(a,\lambda) = \pi a^2 Q(x) \qquad (A.9)$$

where $Q(x)$ is a dimensionless function of $x = 2\pi a/\lambda$.

The following asymptotic limit holds for $Q(x)$:

$$\lim_{x\to\infty} Q(x) = 2 \qquad (A.10)$$

For visible light, $\lambda \approx .5\mu$. If the average particle radius is $\sim 1\mu$ or larger, $x \gtrsim 10$, and the above asymptotic value for $Q(x)$ may be used as a approximation, so that

$$\tau = 2\pi H_a \int_0^\infty n(a,0)\ a^2\ da \qquad (A.11)$$

Assuming that, for an order of magnitude estimate,

$$\frac{\int_0^\infty n(a,0)\ a^3 da}{\int_0^\infty n(a,0)\ a^2 da} \sim \bar{a} \qquad (A.12)$$

where $\bar{a}$ is the mean particle radius, and applying Eq. (A.5) and (A.10) to (A.9), we obtain

$$\tau \sim \frac{3}{2} H_a \Phi(0)/\bar{a} \qquad (A.13)$$

APPENDIX B

THE POLARIZABILITY OF MOLECULES

Most nonpolar molecules, or molecules without permanent dipole moments, have polarizabilities of about the same order of magnitude. The reason is that the induced polarizability of a nonpolar molecule depends primarily on its "size," similar to the way the induced polarizability of a conducting sphere depends on its radius (Eq. (A.1)), and the "sizes" of molecules are roughly the same for ordinary gases. Thus, for example, the polarizabilities of CO_2, N_2, O_2 and argon are 2.93×10^{-24}, 1.74×10^{-24}, 1.57×10^{-24}, and 1.64×10^{-24}, respectively, in units of cm^3.

On the other hand, gases that consist of molecules with permanent dipole moments (polar molecules) may have very large polarizabilities, depending on the magnitude of their permanent moments. The polarizability of a polar molecule consists of an induced part plus another part due to the orientation of its permanent moment; thus,

$$\alpha_{polar} = \alpha_{induced} + \frac{\mu^2}{3kT}, \tag{B.1}$$

where μ is the permanent dipole moment, and k, T are defined previously. The orientation term, $\mu^2/3kT$, has the following meaning: In the absence of a field, the random dipole orientations give a zero average moment; but in the presence of a field E, the dipole orientations in the direction of the field are favored by the Boltzmann distribution, thus leading to a statistical average moment of $+(\mu^2/3kT)\,E$. At ordinary temperatures, say 300° to 600°K, the term $\mu^2/3kT$ is usually much larger than $\alpha_{induced}$. It also means that the polarizability of a polar molecule is usually much larger than the induced polarizability of a nonpolar molecule. As an illustration, consider H_2O, for which Eq. (B.1) reads:

$$\alpha_{H_2O} = \left(1.51 + \frac{8270}{T}\right) \times 10^{-24}\ cm^3, \tag{B.2}$$

where $\mu^2_{H_2O}/3k = 8.270 \times 10^{-21}\ cm^3\ °K$. At 300°K, α_{H_2O} is about ten times α_{CO_2}, and the orientation term in α_{H_2O} is about 18 times the induced term. For simplicity, we will henceforth approximate

$$\alpha_{polar} \approx \frac{\mu^2}{3kT}. \tag{B.3}$$